Star Formation

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Abstract

Centimeter wavelengths observations have the potential of answering long-standing questions about star formation. The physical and chemical properties of key molecules and the very low physical temperatures of pre-protostellar cores conspire to make centimeter wavelength observations essential for observing the structure and deducing the evolution of the progenitors of stars. The ideal instrument would make fully sampled maps about 0.5 deg square with a resolution of about 5 arcsec (about 720 x 720 pixels for Nyquist sampling) with a brightness temperature sensitivity of about 0.1 K and a spectral resolution of about 0.05 km/s.

The sensitivity requirements are almost two orders of magnitude more demanding for observations of the Zeeman effect to determine the magnetic field strength in pre-protostellar clouds, and of observations of complex organic, possibly pre-biogenic, molecules.

Contents

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1 The Origin of Stars and Biochemistry

Although the general process by which clouds turn into stars has been understood with increasing confidence since it was first proposed by [Laplace, 1796], several major questions lack detailed, quantitative answers.

- What initiates the process which results in the formation of a star?
- Why is the efficiency with which molecular clouds are converted into stars as low as it is, $\sim 10\%$ [Zuckerman and Palmer, 1974]?
- Why does the number distribution (initial mass function) of star masses peak at about 0.3 $M_\odot$ [Strom et al., 1993, Strom and Strom, 1994]?
- Why does the initial mass function (IMF), $dN/dM_\odot$, vary as $M_\odot^{-2.35\pm0.20}$ at higher masses [Salpeter, 1955]?
- Why is does the IMF slope change to -1.0 below 1.5 $M_\odot$ [Osorio et al., 1997, Reid and Gizis, 1997]?
- What role does astrochemistry play in the origin of biochemistry?

Star formation regions are difficult to observe because they are very cold, typically 6-10 K, so that even optically thick species emit only weakly, and rare molecular species are very tough to observe. Dilute apertures (interferometer arrays) are unsuitable because they sacrifice surface brightness sensitivity for angular resolution.

1.1 Uncovering the Evolutionary Sequence

One of the key stages in stellar evolution is the period just prior to the formation of a protostar when a cloud core achieves the critical state that transforms it into a collapsing object. The conditions which lead to this transformation, and the processes by which it occurs, determine how solar systems form and how galaxies evolve.

In the commonly presented scenario, a proto-stellar nebula forms out of one of the fragments of a collapsing cloud core. However, recent observations have shown that the medium from which at least some stars form is fragmented on smaller scales [Peng et al., 1998]. It is probable that this is the initial condition for the formation of proto-stellar systems, which then form by the coagulation of many such small fragments.

As illustrated in Fig. 1, at least one pre-protostellar cloud shows evidence for growth by accretion [Kuiper et al., 1996]. Ammonia, which takes about 10^6 year to form [Herbst and Leung, 1989], is concentrated near the center. CCS is a molecule which forms early in a chemically evolving cloud, and is destroyed within a few $\times 10^5$ yr [Millar and Herbst, 1990]. (The astrochemical theory is supported by observations of the infalling protostellar envelope of B335 which show that CCS is present in a layer near the edge of that envelope

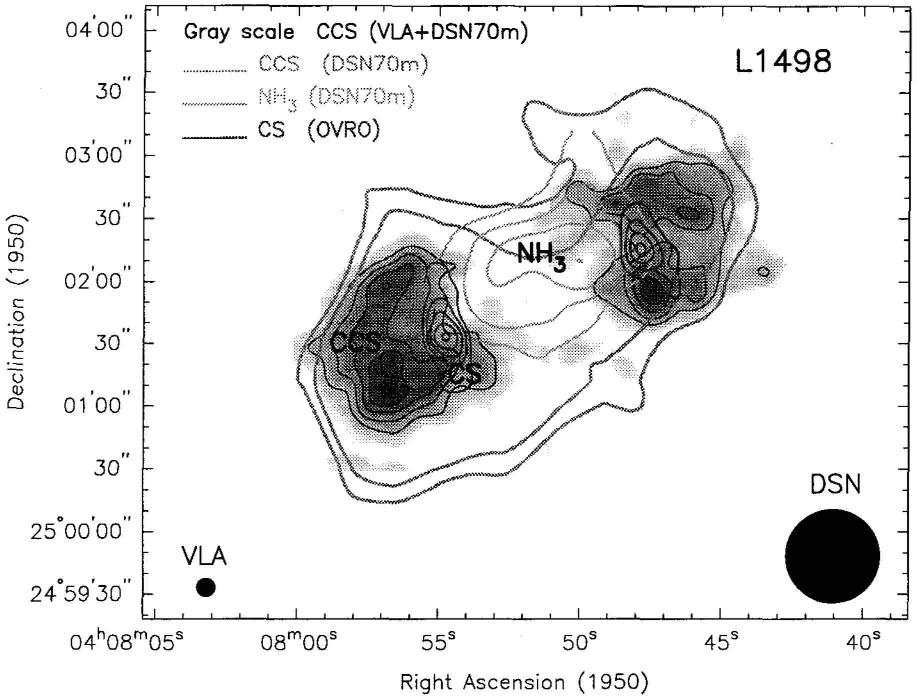

Figure 1: L1498 is an example of a quiescent core, possibly in a pre-protostellar phase. Ammonia, a molecule which forms slowly, is concentrated near the center, indicating the presence of relatively old gas. CCS, a molecule with a short (few $\times 10^5$ yr) lifetime, is concentrated in an outer layer. This suggests that the cloud is growing by accretion.

where the infall starts, and disappears from the gas as it falls towards the center [Velusamy et al., 1995].) Although only the ends of L1498 could be mapped with high angular resolution in the time granted for VLA and OVRO observations, the pattern is strongly suggestive of layering, with the youngest gas on the outside. Not shown in this figure are clumps of small CO gas which surround this cloud. Taken together, these observations reveal a quiescent cloud growing by accretion. Further supporting this picture are ISO observations which show that dust is concentrated at the center where molecules such as $C^{18}O$ are depleted [Willacy et al., 1998]. This cloud appears to be a likely candidate to becoming unstable to collapse, and the site of a future protostar.

If the implied scenario is essentially correct, then the formation of stars is a statistical process. In clouds associated with low mass star formation, fragments of molecular gas with masses in the range of 0.01 to 0.1 $M_\odot$, densities on the order of 10^5 cm^{-3} and temperatures around ≤ 10 K, move with respect to each other with velocities less than the sound speed. These fragments are generally than it is. The number of fragments which must be assembled before a critical mass is obtained should explain why large stars are relatively rare. Assembling the material for stars with larger mass in a time less than the collapse time requires greater densities of fragments, and is therefore less probable. The details of the IMF may be explainable by the mass spectrum of cloud fragments and the probability that such fragments will merge.

A quantitative explanation must be based on the statistics on the cloud clumps which constitute the low mass end of the self-similar structure of the interstellar molecular medium. Sensitive ($T_A^* \sim 0.1$ K) spectral line maps of molecular clouds, with high spectral resolution (~ 0.05 km s^{-1}) and high spatial resolution (5-10 arcsec for the nearby star-forming clouds), are required to provide the statistical data on the density, mass, and temperature of the fragments, the space density of the fragments and their relative velocities. Comparison of the abundances of key molecular species can provide information on the ages of fragments, and yield an evolutionary sequence as the abundances respond to the changing conditions during the pre-star-formation assembly process.

1.2 The Key Role of the SKA

Observations of this type are best done at centimeter wavelengths. In fact, it can be argued that extensive cm-λ observations are essential. In dark cloud cores, CCS and NH_3 abundances are anti-correlated, with NH_3 abundant in cores with signs of star formation, and CCS abundant in cores without star formation [Suzuki et al., 1992]. These then are two key molecules which probe the beginning and end of the star formation evolutionary sequence. At these low temperatures ammonia only emits significantly in a few transitions near 24 GHz. CCS and similar carbon chain molecules, because of their large moments of inertia, radiate predominantly at centimeter wavelengths.

Taurus MC1 illustrates the need for the SKA in studying star formation (Fig. 2). Over a region about 20 arcmin in size, the evolutionary sequence appears to be laid out, presenting us with a Rosetta Stone for unravelling the process by which low mass stars form. At the NW end, there are a concentration of NH_3, IRAS, and outflow sources [Chandler et al., 1996]. At the SE end, young CCS gas predominates. There are five condensations, labelled A through E, along the cloud and star formation is evident only near core A. It seems likely that, in time, star formation will occur, probably sequentially, in at least some of the other condensations. It may be that these cores lay out an evolutionary sequence for star formation. However, with the best present instrumentation, it took several years and several hundred hours of telescope time to observe Core D alone.

Existing telescopes and arrays are not well suited to measuring on the relevant size scales (see Fig. 3). The largest single apertures do not have enough resolution, and the arrays don't pack enough dishes close enough together to achieve the required aerial coverage and sensitivity.

The sensitivity requirement argues strongly against dilute apertures. With a 50 K system temperature, it takes about an hour to integrate to an r.m.s noise

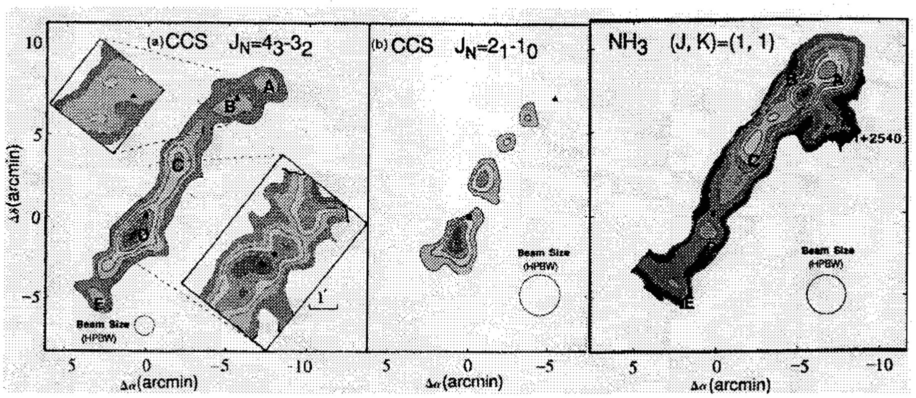

Figure 2: Taurus Molecular Cloud 1 shows a linear progression from young CCS-rich gas in the SE to older gas with prominent NH_3 in the NW. (Adapted from original [Hirahara et al., 1992].)

achieve the required aerial coverage and sensitivity.

The sensitivity requirement argues strongly against dilute apertures. With a 50 K system temperature, it takes about an hour to integrate to an r.m.s noise level of 0.03 K with a spectral resolution of 0.05 km/s at 22 GHz with a filled aperture. However, single pixel observations take too long. TMC1 suggests a minimum requirement for practical star formation research – the ability to map one core fully in one spectral line in one pass. This would require a 100×100 pixel Nyquist-sampled map 5 arcmin on a side. At 22 GHz, a array of 10-m antennas with a maximum spacing of 500 m, for example, would meet this requirement. Because we assume a full pass, say eight hours, to make the map, a small amount of aperture dilution could be tolerated, if the actual system temperature is not greatly different from the 50 K assumed in the above calculation.

Ideally, one would map the entire cloud, covering 0.5°, in one pass in several spectral lines or transitions. This would enable astonishing progress towards a truly quantitative understanding of star formation.

For observations of cold cloud core spectra, a resolution of $\sim$ 0.05 km/s over a 1 km/s band, or about 200 channels, would be ideal for studying the early stages of star formation. The spectral resolution is needed to analyze the individual line components, and the spectral coverage for complex sources like TMC which have multiple spectral features.

2 Pre-Biotic Interstellar Chemistry

The relationship between linear carbon chains such as carbenes (H_2C_X), carbynes (HC_X), and cyanopolyynes (HC_XN) and polyaromatic hydrocarbons (sheet-like molecules based on benzene rings) is likely to be the key to understanding

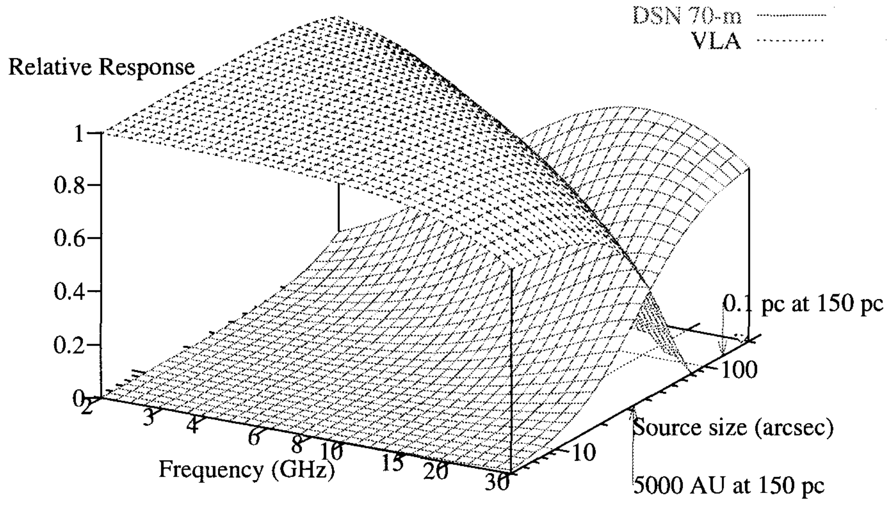

Figure 3: The physical size scales relevant to star formation in the nearest star forming regions correspond to angular scales just below the beamsize of the NASA 70-m and MPIfR 100-m, and large enough that VLA is insensitive the larger structures. For example, the Oort Cloud ranges from about 10,000 AU to 0.5 pc.

the origin of complex organics in interstellar clouds. Extensive observations of the abundances of complex organics at various stages of pre-protostellar evolution are required to identify the specific astrochemical processes which determine the composition of the material from which protostars and their accompanying nebulae.

It is possible that current observations are at a significant sensitivity threshold. Laboratory measurements of the production of cyanopolyynes show that the relative abundance flattens when there are more than nine carbons, reaching at asymptotic value only factor of ten less for more than 15-17 carbons [McCarthy et al., 1998]. However, because the energy is distributed over many more transitions, the intensity per line still decreases, requiring greater telescope sensitivity. Since the moment of inertia increases with more carbons, all transitions with any significant population will be at centimeter wavelengths.

The origin of the diffuse interstellar bands (DIBs) has been a mystery since their discovery many decades ago. It has been suggested that "cumulenes" are the carriers of the DIBs. Cumulenes are carbon chains with double bonds, instead of the alternating single/triple bonds of the known interstellar carbon

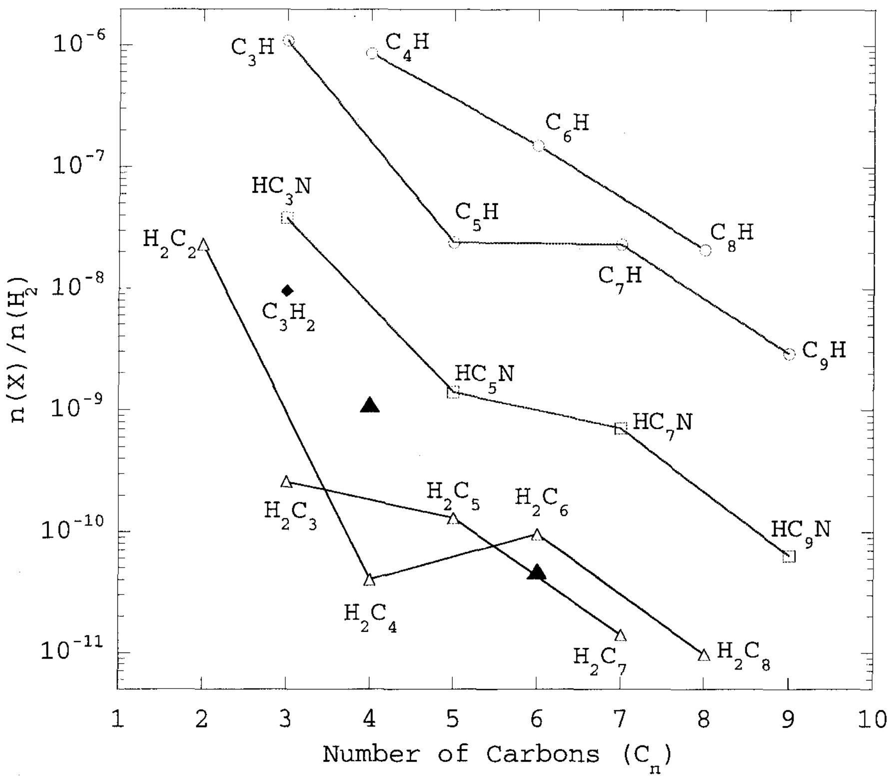

Figure 4: The predicted and observed abundances of various carbon-chain species from Langer et al (1997) illustrates the need for greater senstivity in the study of interstellar organic chemistry. Carbenes are colored blue with the solid triangles representing observed abundances. The black diamond is a measurement of cyclopropenylidene, a ring-shaped molecule. Carbynes are colored red, and cyanopolyynes green.

chains. The longest cumulene currently known to occur in pre-protostellar clouds is H_2C_6, in which it has an abundance of 4×10^{-11} [Langer et al., 1997]. As shown in Fig. 4, H_2C_8 will probably have an abundance of $\sim 4 \times 10^{-12}$ and a brightness temperature of ~ 1 mK, requiring a very sensitive telescope.

At the low temperatures of these clouds, such molecules radiate most of their energy at centimeter wavelengths. It is important therefore that the SKA be very sensitive to brightness temperature. Though it may be hard to achieve the per-pixel sensitivity of a HEMT or MASER equipped telescope, it offers a potentially significant advantages. Because of its higher angular resolution it will be better coupled to the small source regions where the emission originates, assuming that the SKA is not a dilute array. Also, we have no *a priori* knowledge of where these emission peak. Observations have shown that because the regions emission and allow the different evolutionary stages of closely adjacent regions to be studied.

For searches for new spectral lines whose frequencies may be uncertain, a resolution of ~ 0.15 km/s is optimal, and one would want to be able to trade angular resolution (i.e. give up some longer baselines) for wider spectral coverage using more more spectral channels.

3 Measurements of Magnetic Field Strength

The molecule CCS, which is abundant in newly formed gas present when star formation begins, is subject to a substantial Zeeman effect which can be used to measure the strength of the line-of-sight component of the magnetic field. The CCS Zeeman effect may well be the best if not the only tool for determining the strength of the magnetic field in cloud cores at the stage where protostellar collapse might occur. Knowledge of the magnetic field strength is essential for determining how collapse may be prevented or slowed by magnetic pressure. The transition which has the greatest sensitivity to this effect is at 11.119 GHz. The measurements require high sensitivity and high spectral resolution to make very precise determinations of line profiles, and high angular resolution to resolve the magnetic structure in protostellar cores. Present efforts to observe this effect with single aperture telescopes involve many tens of hours of integration time for one position.

A 1000-m diameter telescope operating at 11 GHz would have a beam of ~ 7 arcsec at 11 GHz, ideal for resolving the various domains in nearby star forming regions. A telescope half or even a third that size is probably adequate for studying the nearest (~ 150 pc) sources.

The effect being sought is extremely weak and easily masked by systematic instrumental effects. Interferometry has an advantage because it reduces spectral baseline effects. However, aperture dilution and less than optimal receiver temperatures are very undesirable, since it is unclear how much these can be offset by longer integration times.

4 Summary

A next generation cm-λ telescope is crucial to resolving long standing and crucial questions about how stars form. A data rate increase of about two orders of magnitude is necessary to acquire the necessary statistics. This cannot be done at the expense of sensitivity however, since the sources have very low brightness temperatures. Large, filled apertures are essential.

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